The Chronology of Large Lunar Impacts and the Late Heavy Bombardment Hypothesis

Charley Lineweaver &
Marc Norman
Planetary Science Institute
Australian National University

Norman & Lineweaver 2007, 2008

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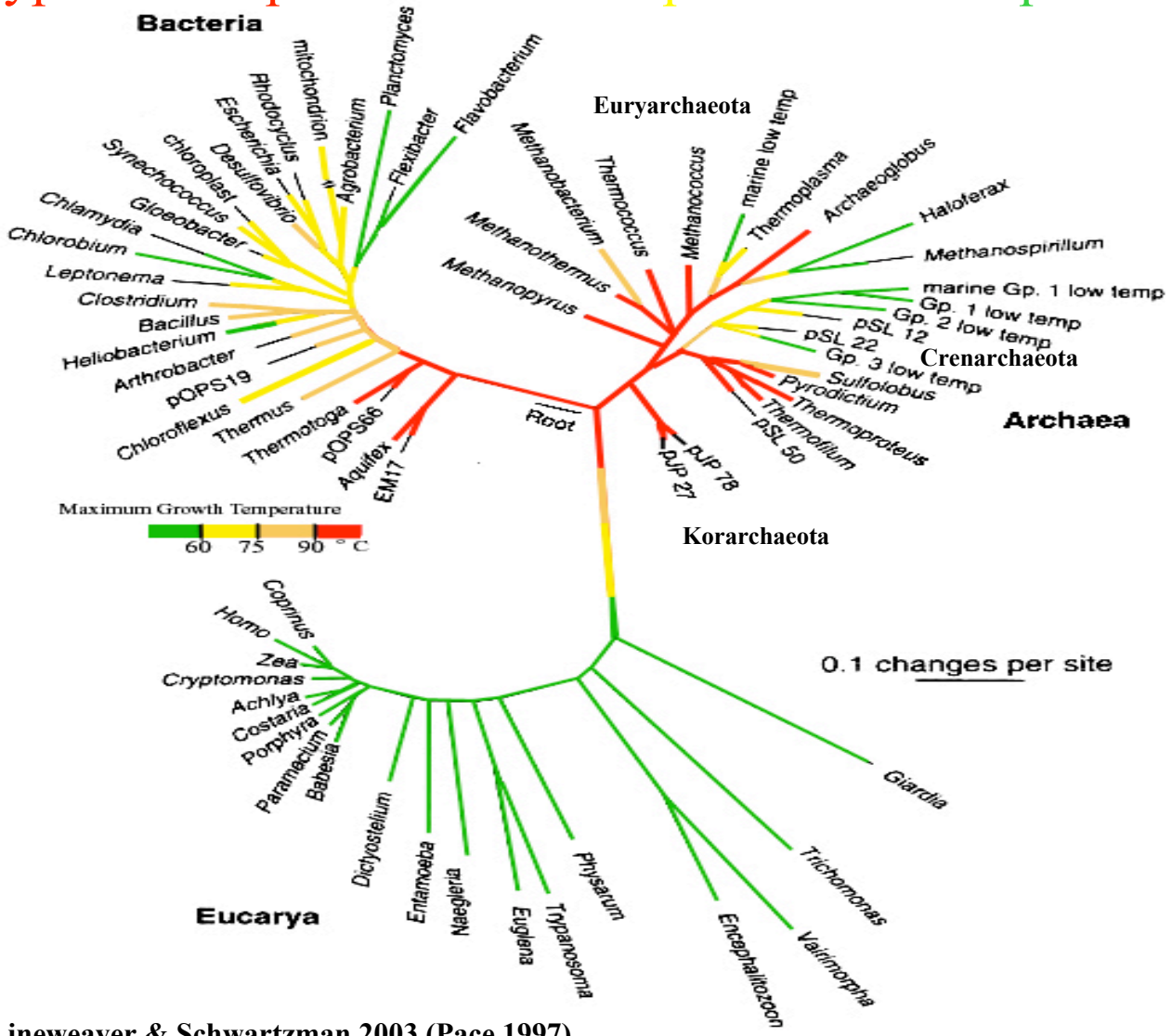
Towards a natural system of organisms: Proposal for the domains Archaea, Bacteria, and Eucarya

(Euryarchaeota/Crenarchaeota/kingdom/evolution)

CARL R. WOESE*†, OTTO KANDLER‡, AND MARK L. WHEELIS§

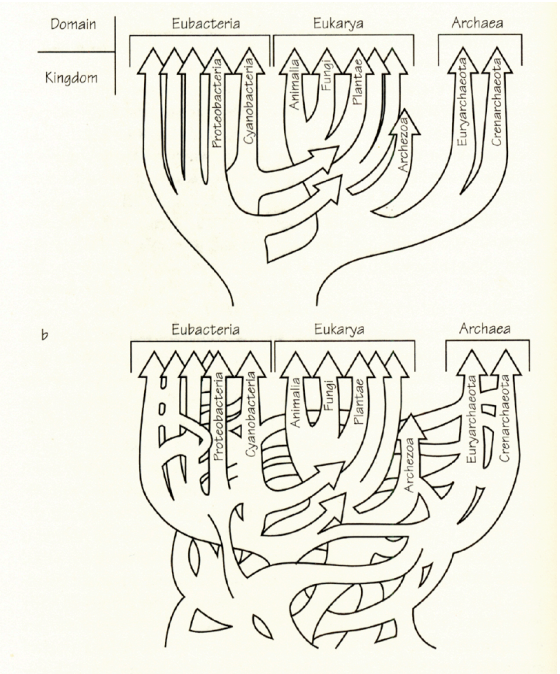
PNAS 1990

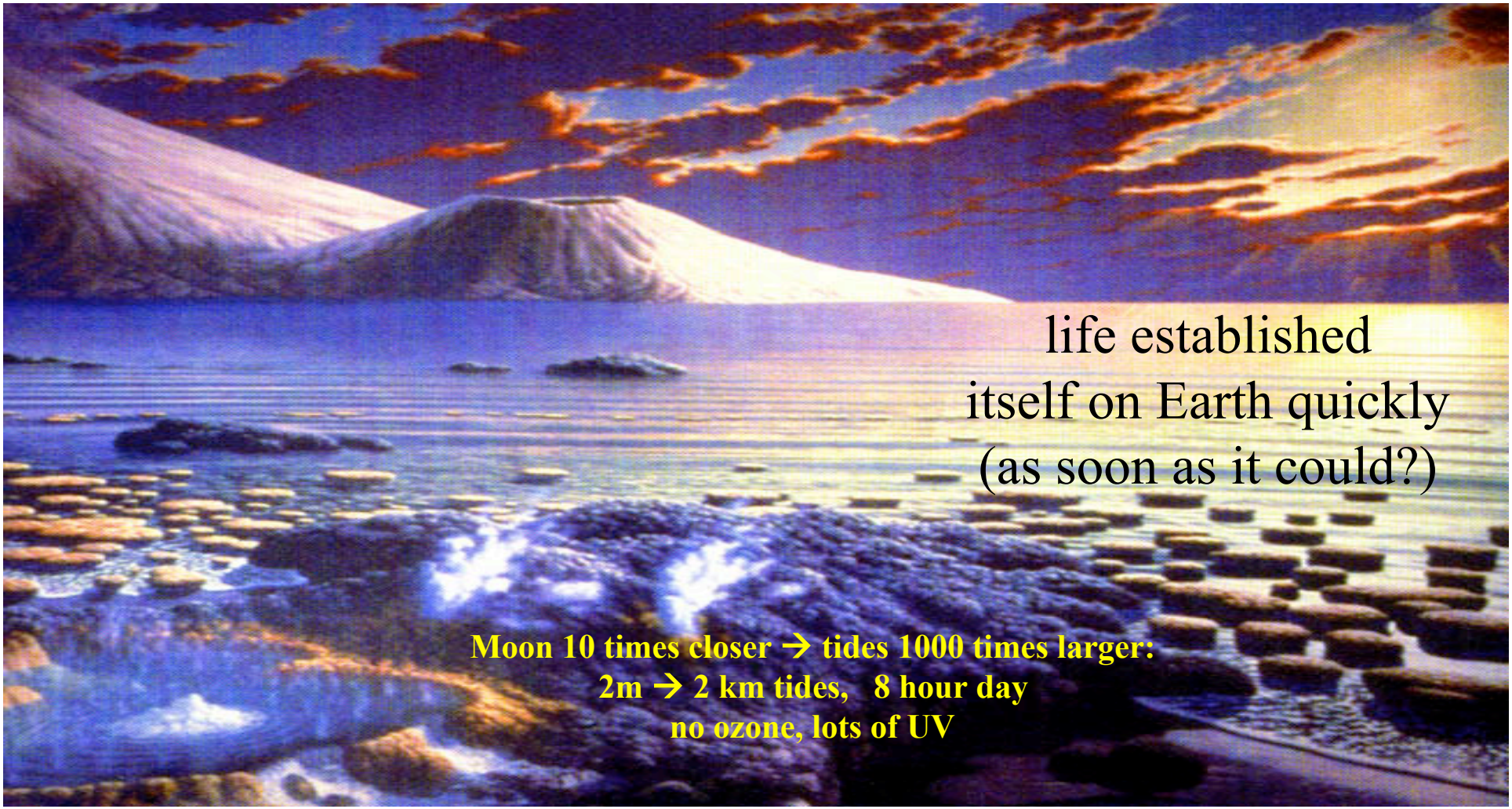
hyperthermophiles → thermophiles → mesophiles

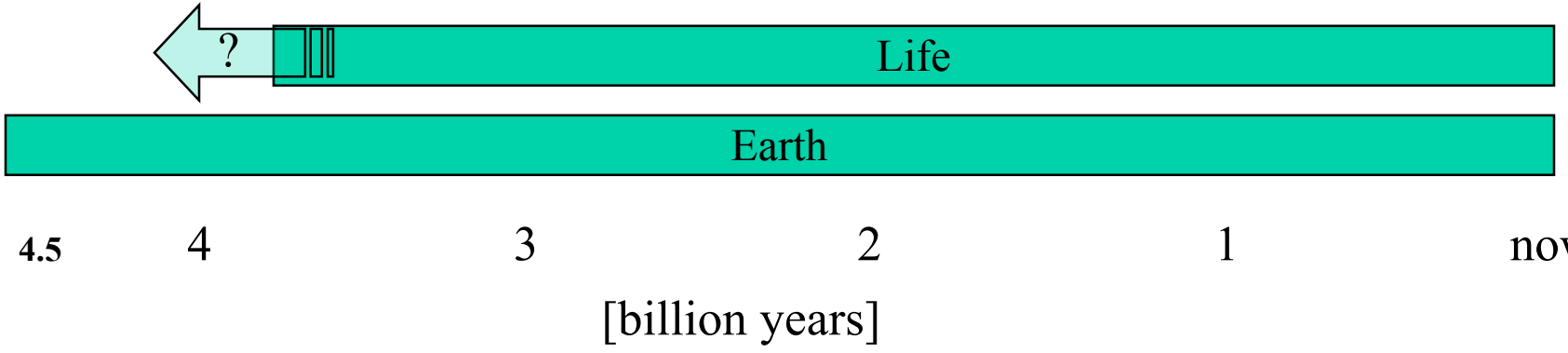


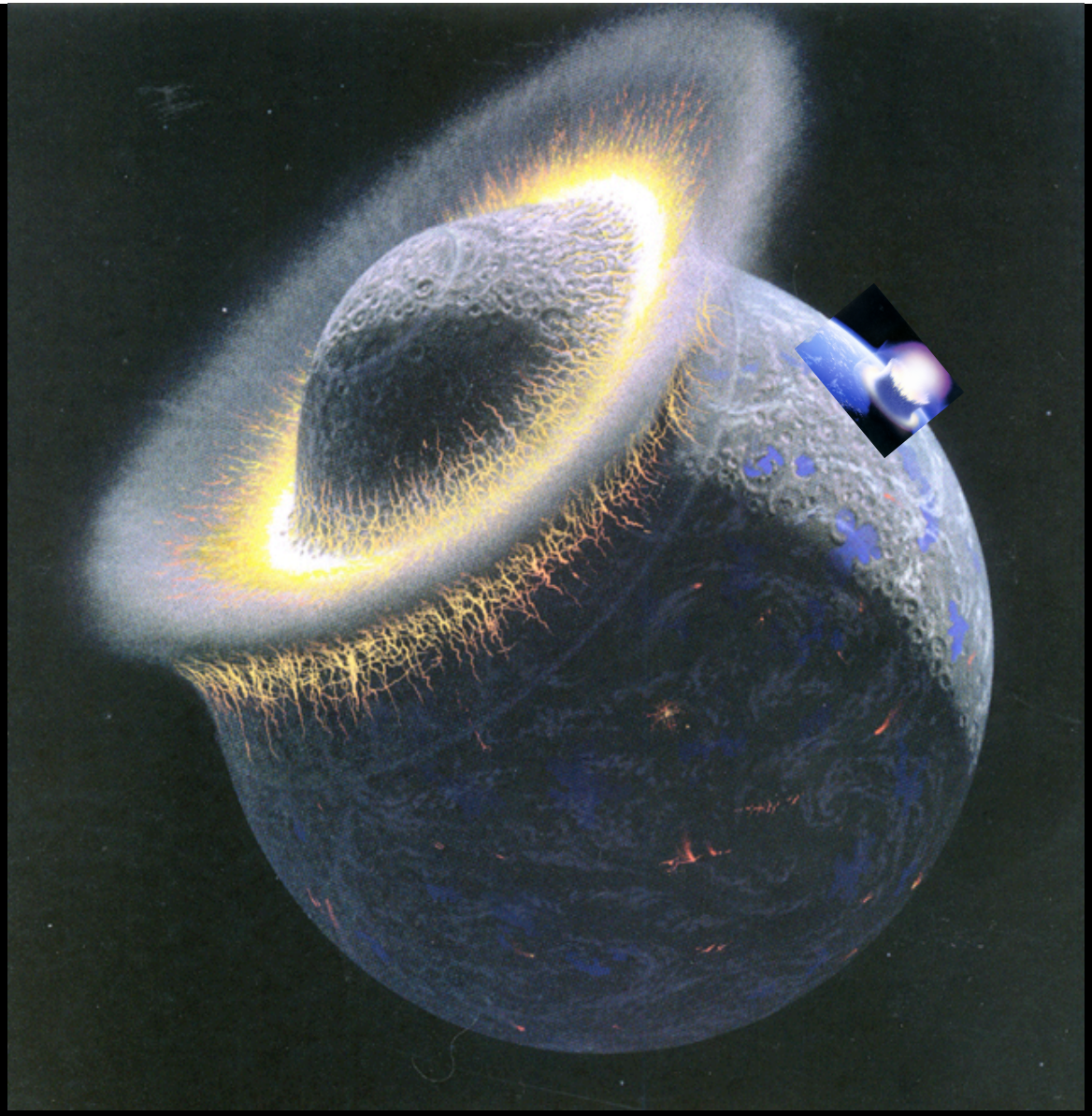
Lineweaver & Schwartzman 2003 (Pace 1997)

Carl Woese



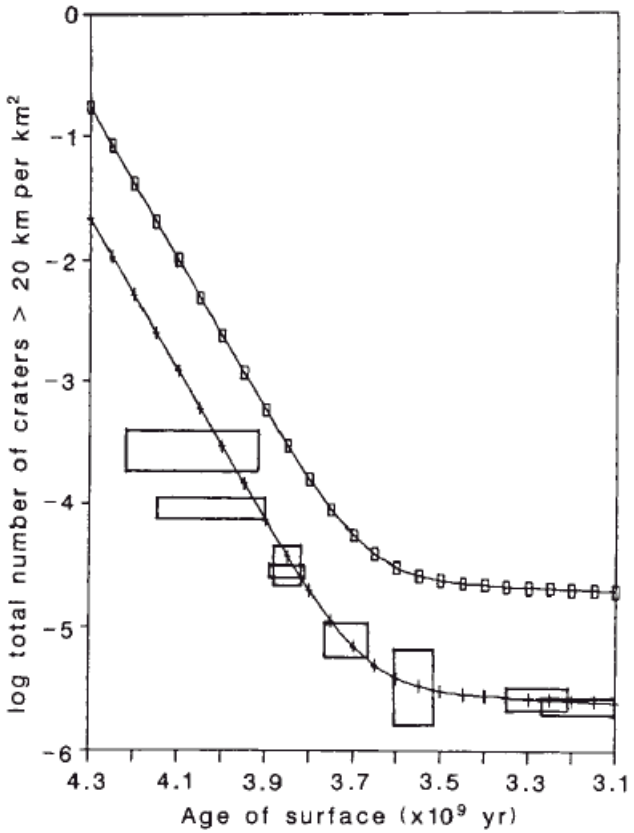

life established
itself on Earth quickly
(as soon as it could?)
Moon 10 times closer → tides 1000 times larger:
2m → 2 km tides, 8 hour day
no ozone, lots of UV


?
Life
Earth
4.5
4
3
2
1
now
[billion years]



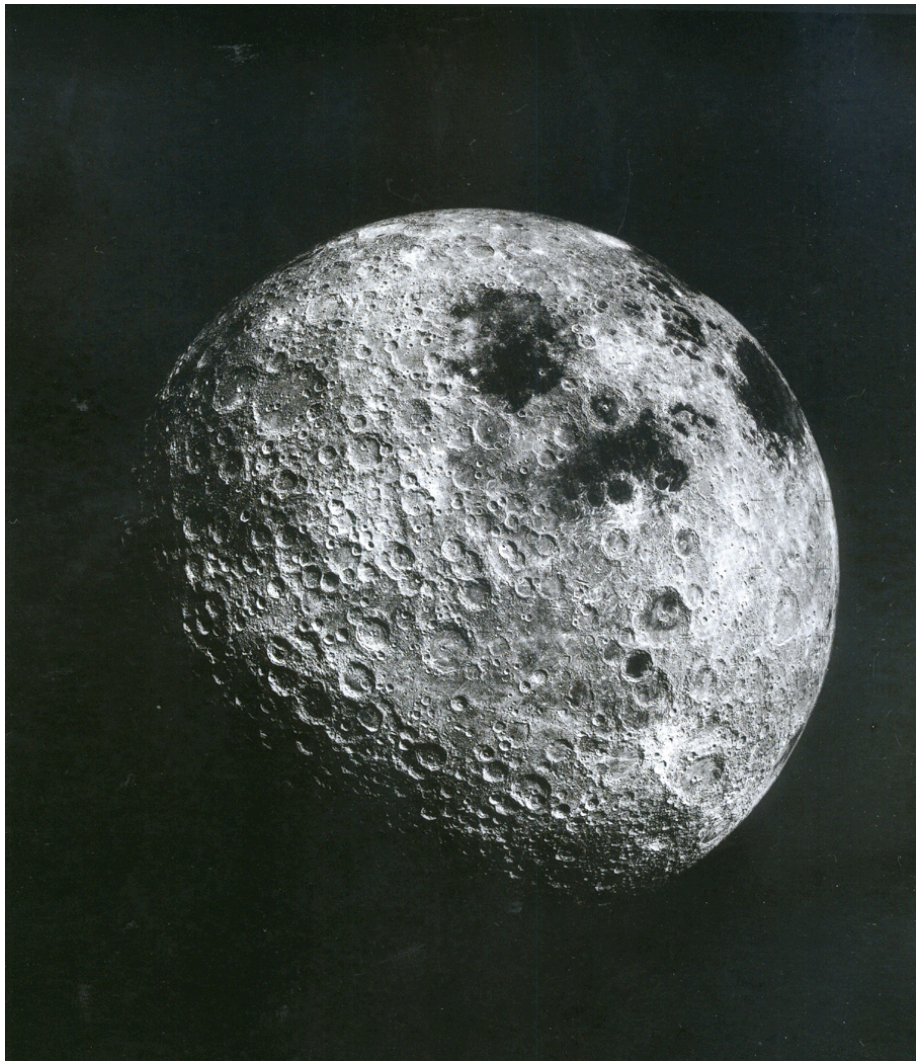
Quantifying the impact frustration of life using the Moon as a bombardometer

Maher & Stevenson 1988
Sleep & Zahnle 1998



Earth

Moon



"…the Earth will likely suffer ~ 10 impacts by objects more massive than any that strike the Moon." Hartman et al 2000

~500 km

If Byrnes (2007) is right about a near side megabasin (D ~ 6000 km) then ~10 impacts could have frustrated biogenesis on the early Earth

"Finding a Second Sample of Life on Earth"

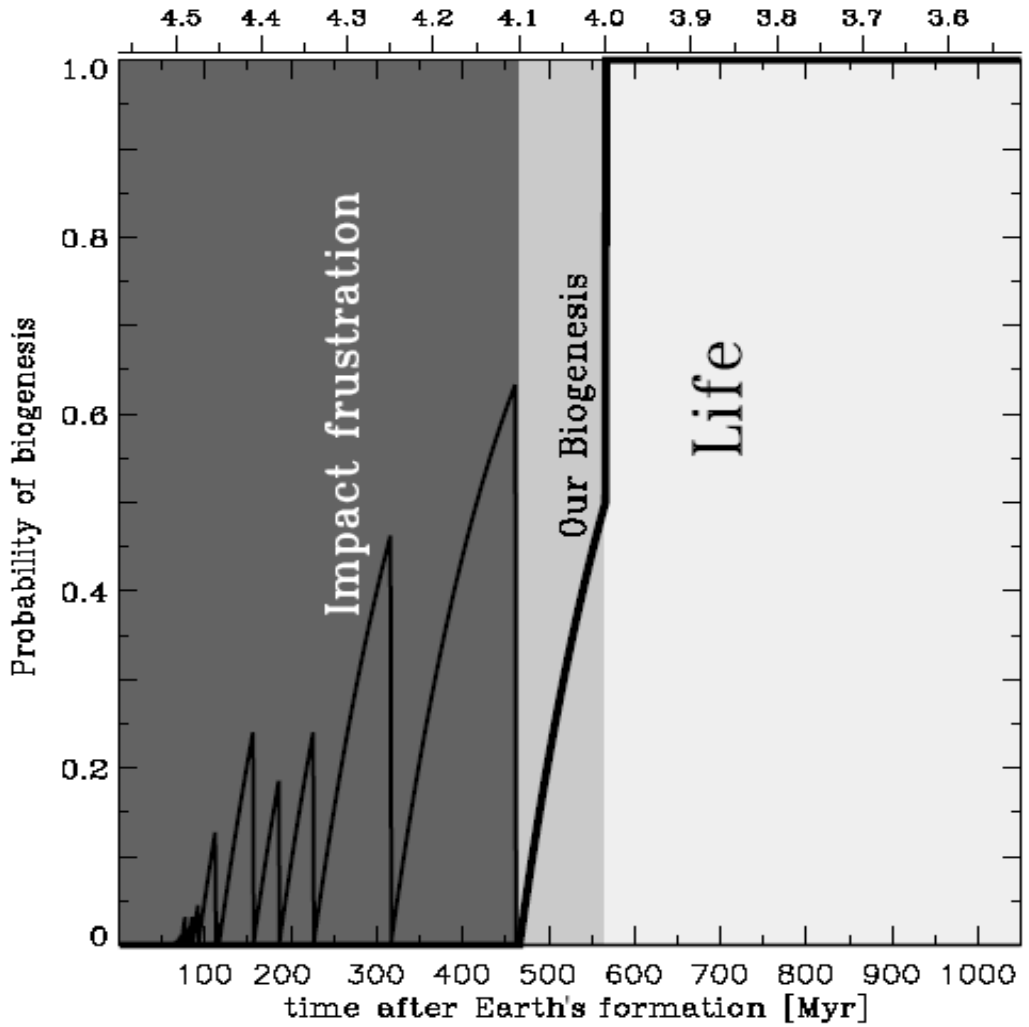
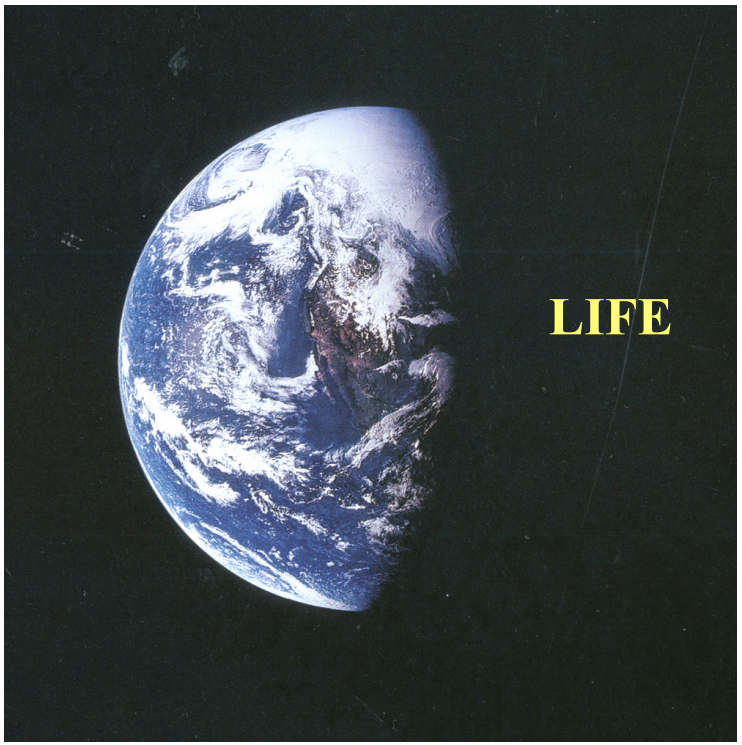


FIG. 1. The probability of biogenesis during multiple and increasingly longer quiescent periods of the first billion years of Earth's history. As an example, we show known life having formed between 4.1 and 4.0 Gyr ago and then resisting extinction from subsequent impacts that included the late heavy bombardment (3.8–3.9 Gyr) associated with the largest lunar mare. It was assumed that periodic large impactors (diameter $D > 500$ km) sterilized the Earth and eliminated any life that may have emerged (Sleep *et al.*, 1989) prior to biogenesis (assumed to have been a process of molecular evolution). The time period of biogenesis, $\Delta t_{\text{biogenesis}}$, was estimated to be 100 Myr [see Lineweaver and Davis (2002) for a review of estimates of this time scale]. The probability of biogenesis during $\Delta t_{\text{biogenesis}}$ was estimated at 50% ($q = 0.5$ in Fig. 3 of Lineweaver and Davis, 2002). In this example the probability of at least one epoch of a second biogenesis is ~0.9 (see Appendix for mathematical details).

Finding a Second Sample of Life on Earth

If life emerges readily under Earth-like conditions, the possibility arises of multiple terrestrial genesis events. We seek to quantify the probability of this scenario using estimates of the Archean bombardment rate and the fact that life established itself fairly rapidly on Earth once conditions became favorable. We find a significant likelihood that at least one more sample of life, referred to here as alien life, may have emerged on Earth, and could have coexisted with known life. Indeed, it is difficult to rule out the possibility of extant alien life. We offer some suggestions for how an alternative sample of life might be detected. Key Words: Origin of life—Biogenesis—Impact frustration. Astrobiology 5, 154–163.

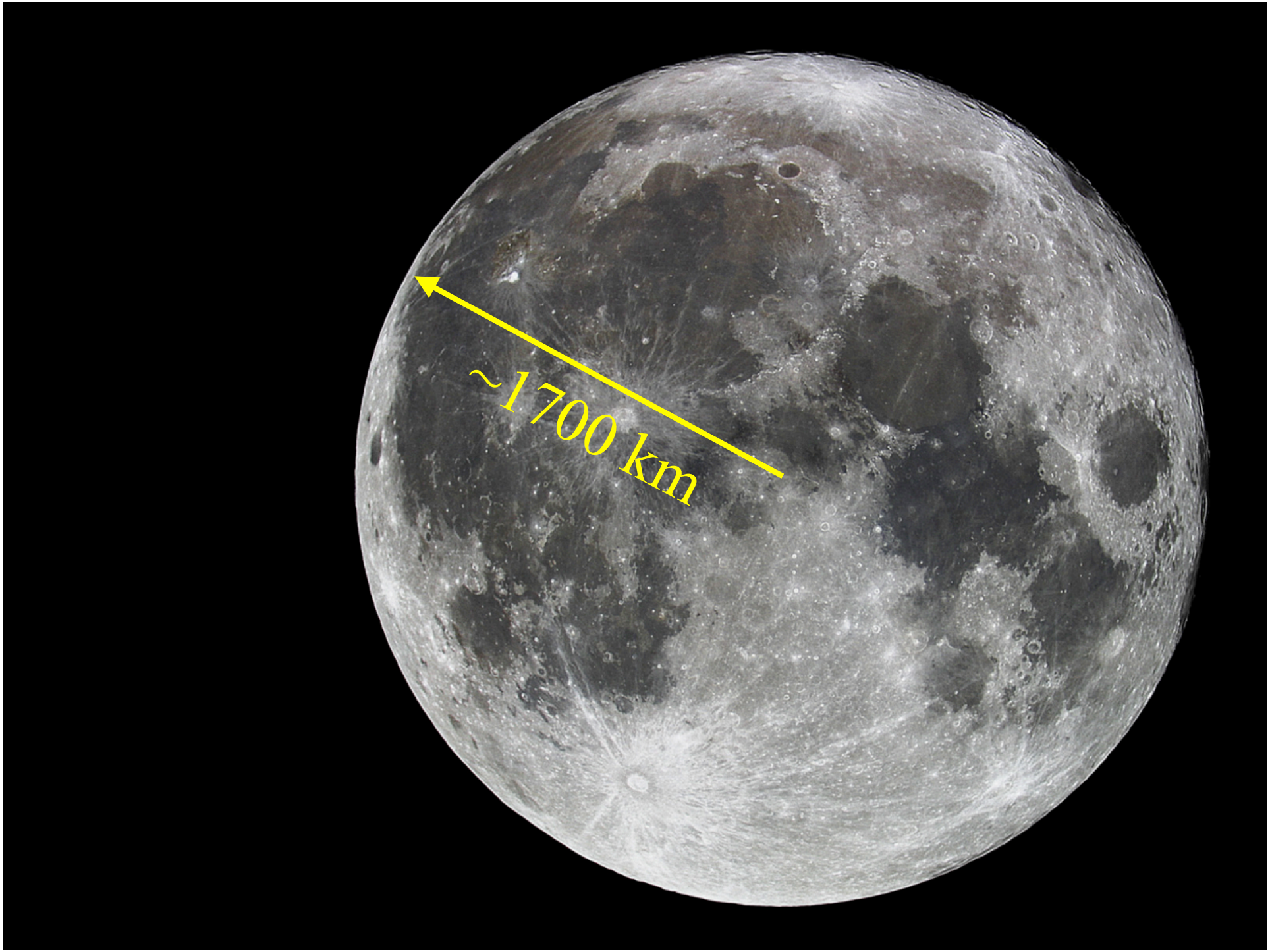
Davies & Lineweaver, 2005, Astrobiology



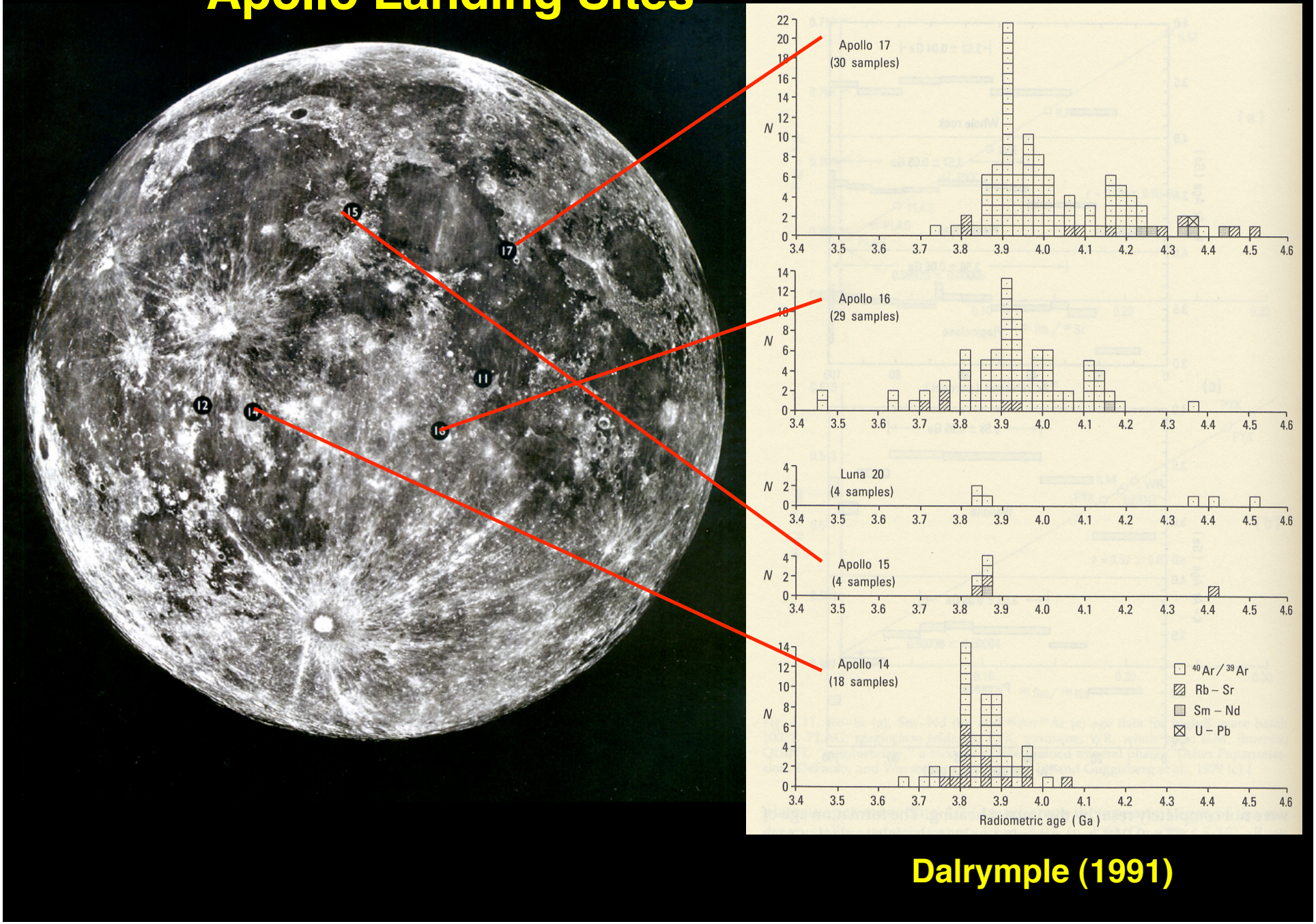
?

impact extinction

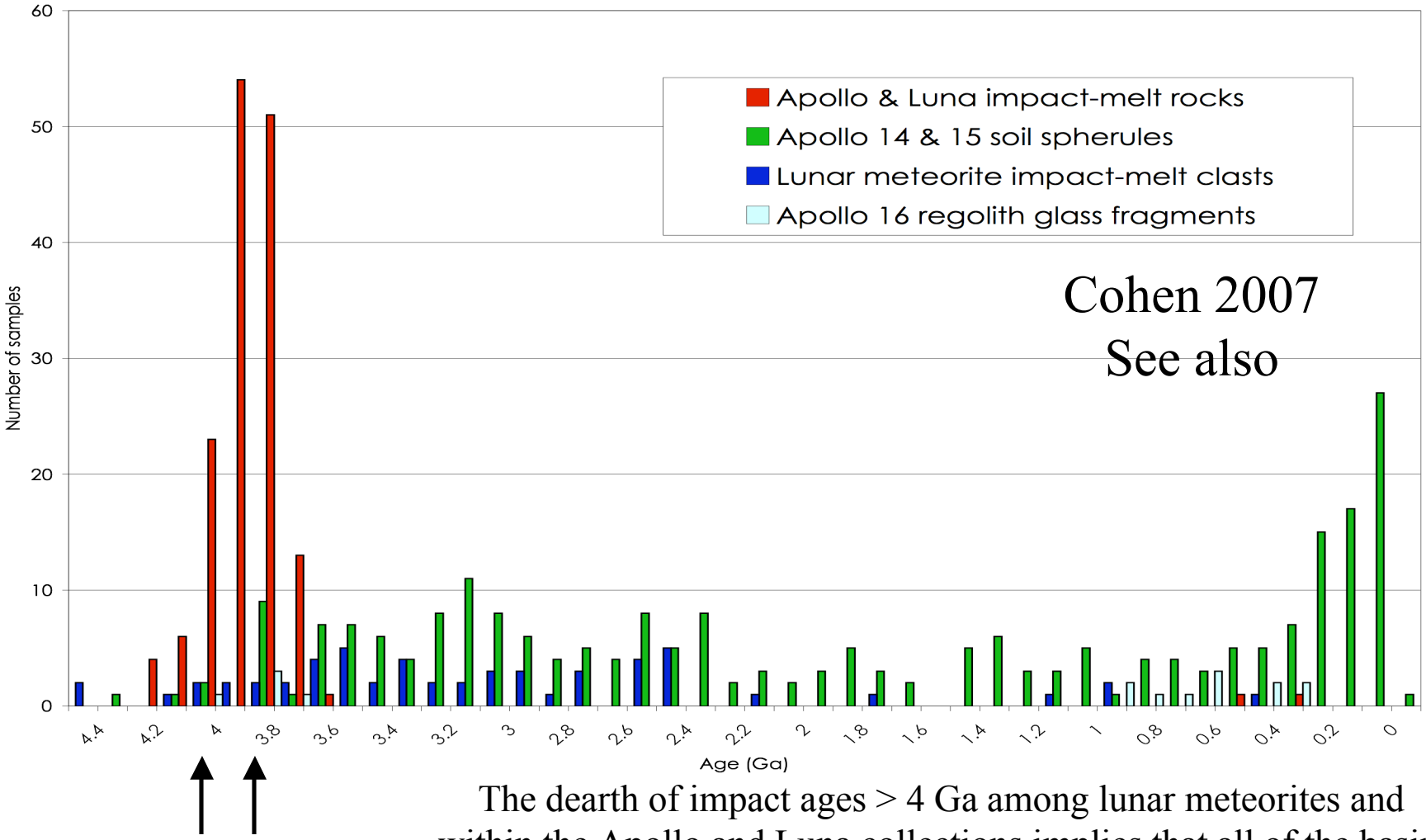
impact extinction


~1700 km

Apollo Landing Sites



Dalrymple (1991)



The dearth of impact ages > 4 Ga among lunar meteorites and within the Apollo and Luna collections implies that all of the basins including those in the Pre-Nectarian Period were produced in the same narrow window of time 3.85-4.05 Ga. (Kring poster)

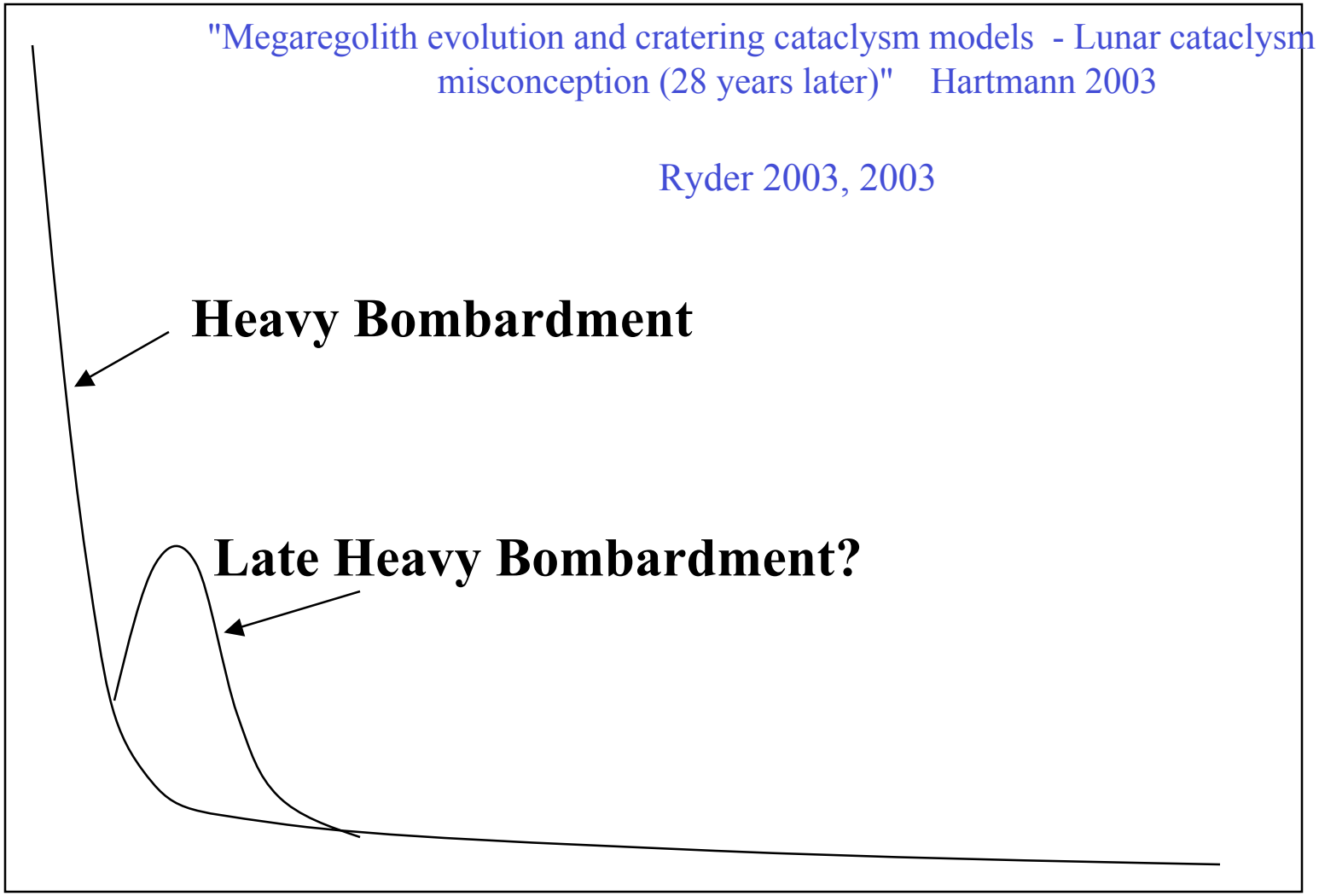
"A few have older ages [than ~3.9] (Bogard 2005)
hough not enough to suggest a heavy bombardment earlier."
Swindle et al 2005

Impact rate

"What are the real constraints on the existence and magnitude of the late heavy bombardment?" Chapman, Cohen and Grinspoon 2007

"Megaregolith evolution and cratering cataclysm models - Lunar cataclysm as a misconception (28 years later)" Hartmann 2003

Ryder 2003, 2003



The Geologic History of the Moon

By **DON E. WILHELMS**

with sections by **JOHN F. McCAULEY**
and **NEWELL J. TRASK**

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1348

A comprehensive review of lunar science and evolution from the viewpoint of historical geology, based on data from both photogeologic observations and lunar-sample analysis

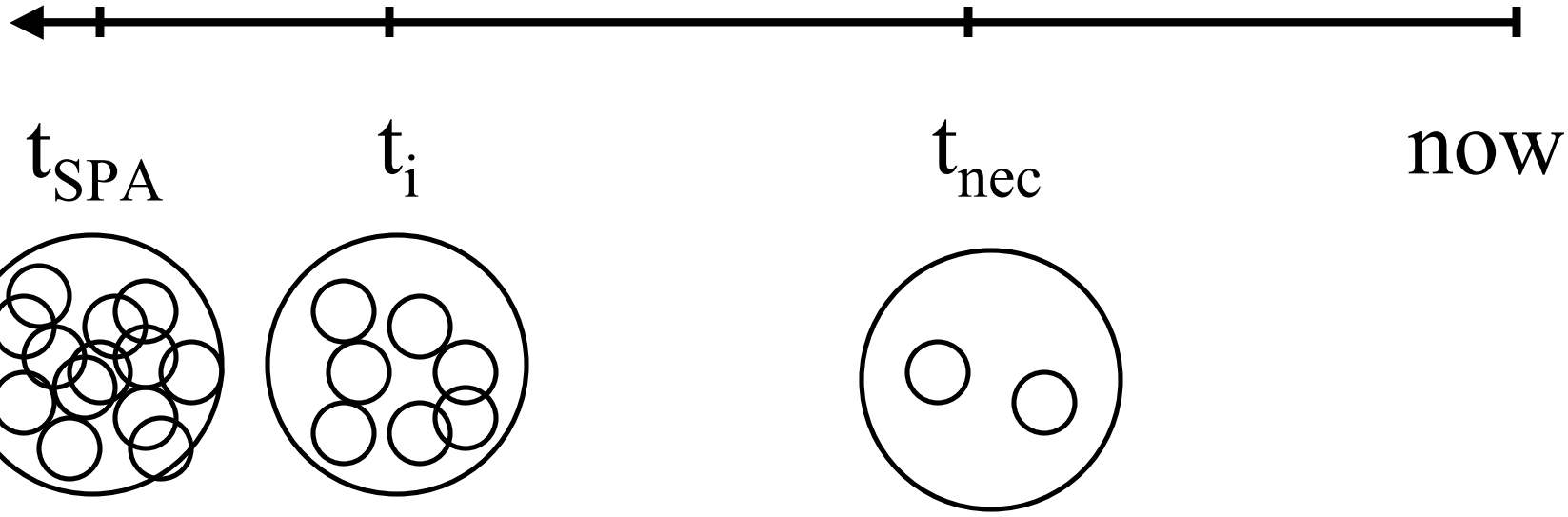
CONTENTS

Cumulative crater densities (D > 20 km) inside basins (D> 300 km) are from Wilhelms 1987, Table 8.2, Fig. 8.6, Table 9.3 and Fig 9.22
Crater diameters are from Wood 2004, Impact Basin Database

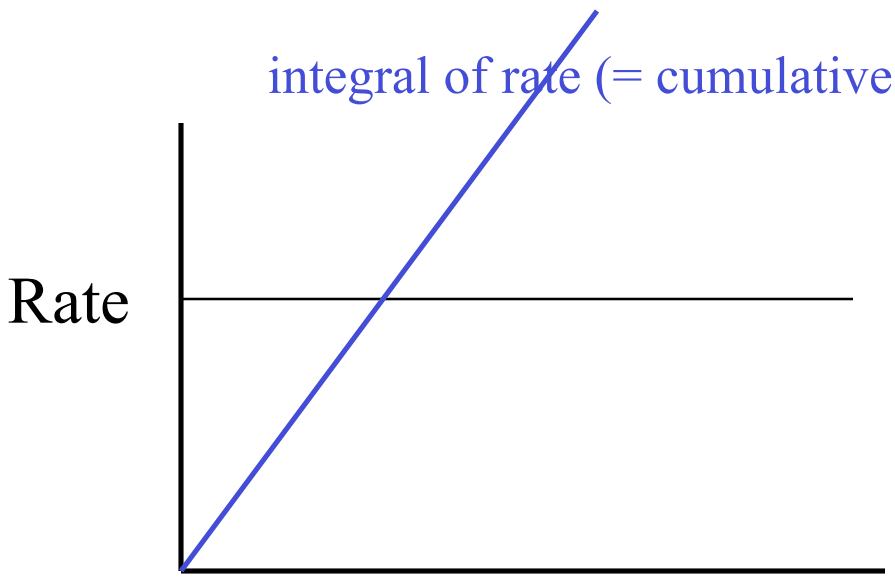
We used crater densities to assign relative ages, which are then assigned absolute ages based on three assumptions about the ages of Imbrium, Nectaris and SPA

$$t_i = t_{nec} + (\rho_i - \rho_{nec})/R$$

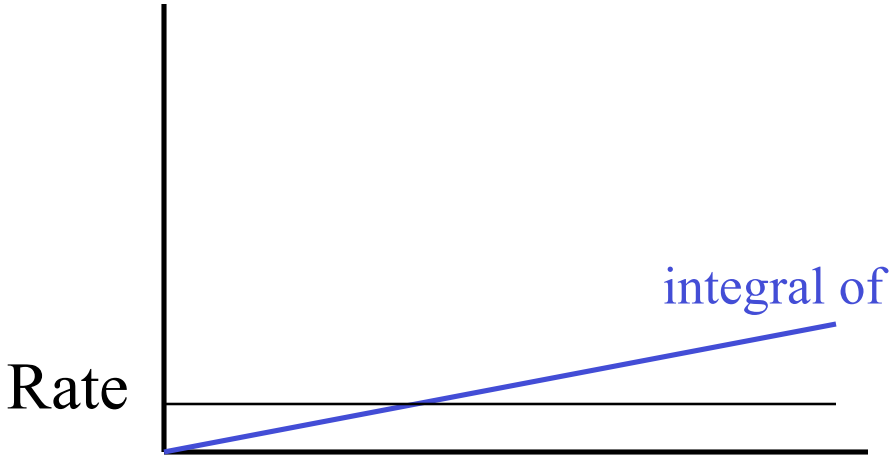
$$R = (\rho_{SPA} - \rho_{nec}) / (t_{SPA} - t_{nec})$$



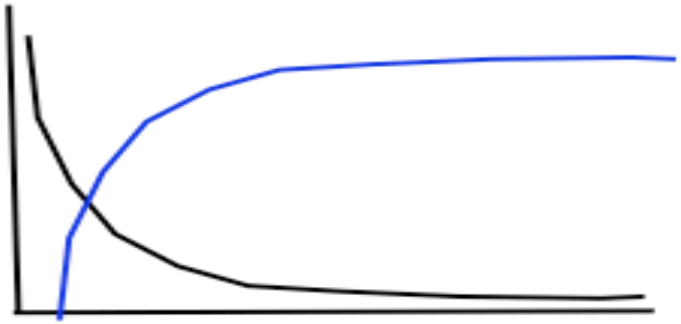
$$\rho_{SPA} > \rho_i > \rho_{nec}$$

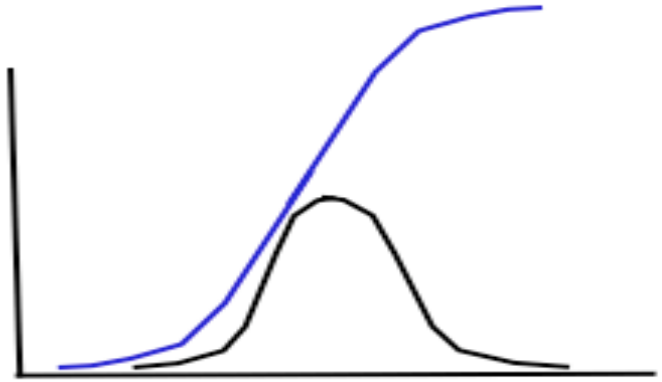


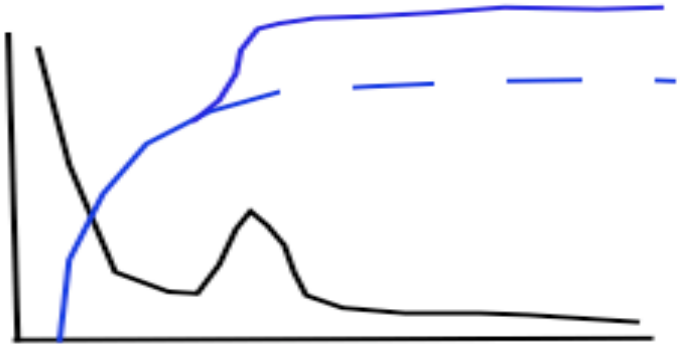
high rate ↔ steep slope

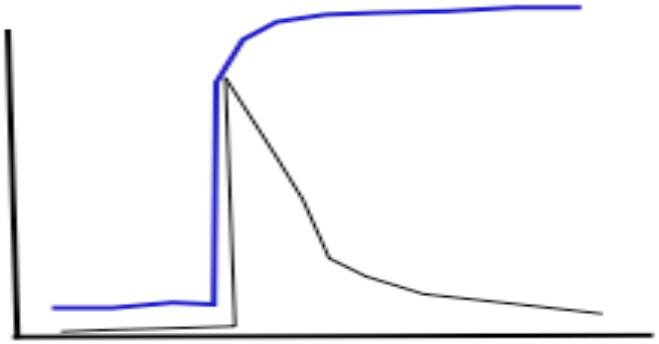


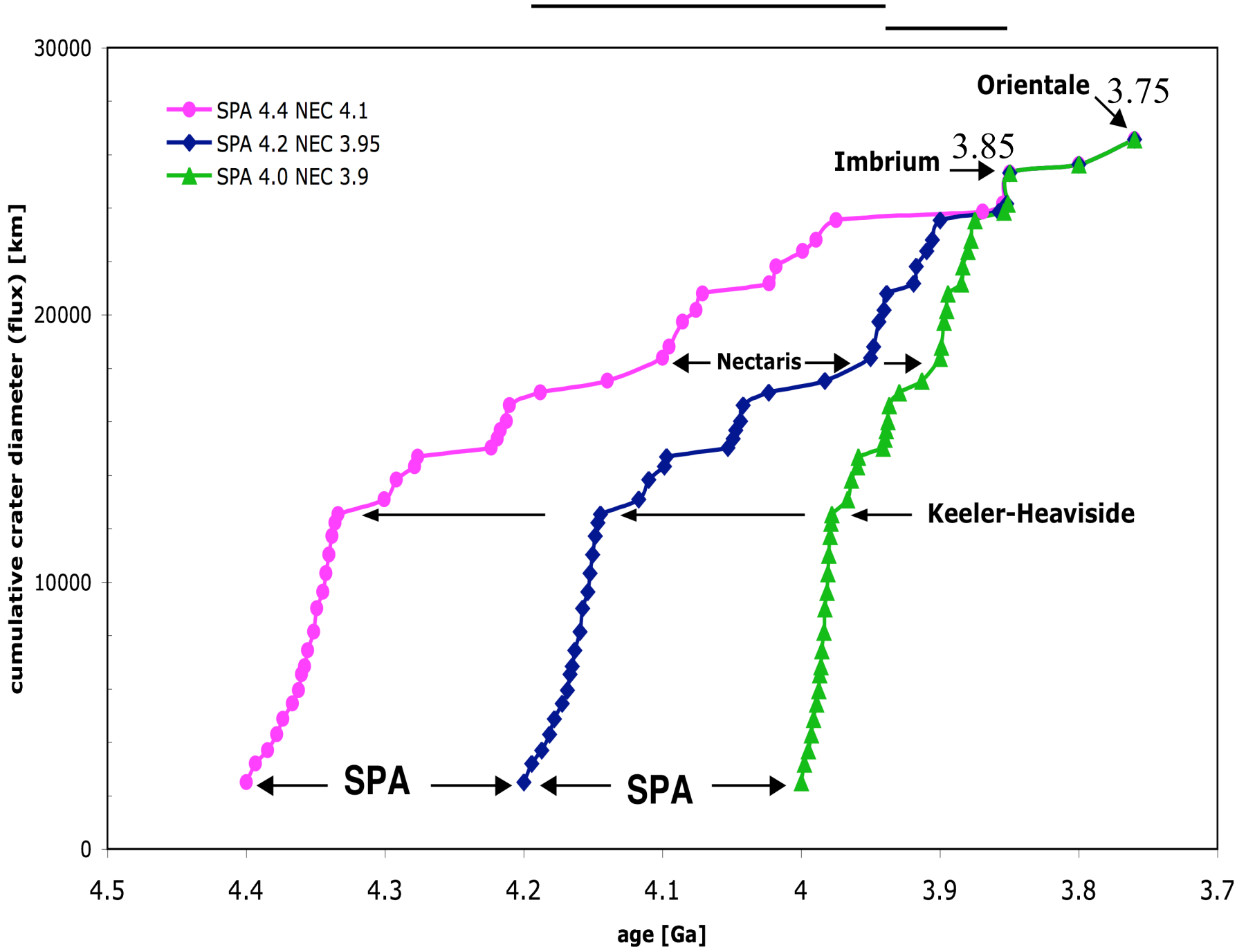
low rate ↔ shallow slope

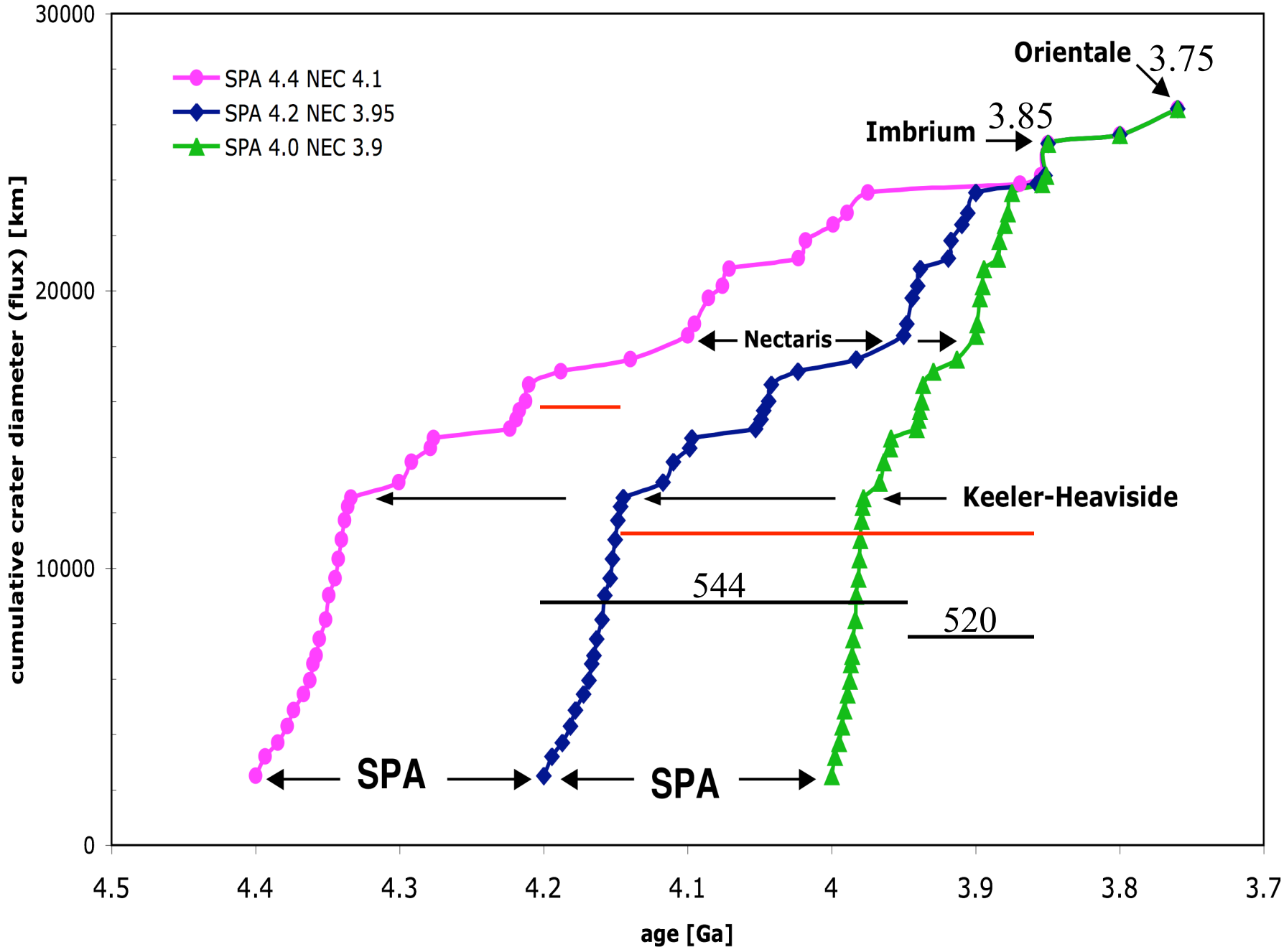









SPA 4.4 NEC 4.1
SPA 4.2 NEC 3.95
SPA 4.0 NEC 3.9
Orientale 3.75
Imbrium 3.85
Nectaris
Keeler-Heaviside
SPA
SPA
cumulative crater diameter (flux) [km]
30000
20000
10000
0
4.5
4.4
4.3
4.2
4.1
4
3.9
3.8
3.7
age [Ga]


SPA 4.4 NEC 4.1
SPA 4.2 NEC 3.95
SPA 4.0 NEC 3.9
Orientale
3.75
Imbrium
3.85
Nectaris
Keeler-Heaviside
544
520
SPA
SPA
cumulative crater diameter (flux) [km]
30000
20000
10000
0
4.5
4.4
4.3
4.2
4.1
4
3.9
3.8
3.7
age [Ga]

Orien	Imb	dt	Nec	dt	SPA
3.75	3.85	0.05	3.9	0.1	4.0
	3.85	**0.1**	**3.95**	**0.25**	**4.1**
	3.85	0.25	4.1	0.3	4.4

Number of craters with D> 20 km per 10^6 km^2

Orien	Imb	R	Nec	R	SPA
16	27		79		215
		1040		1360	
		520		**544**	
		208		453	

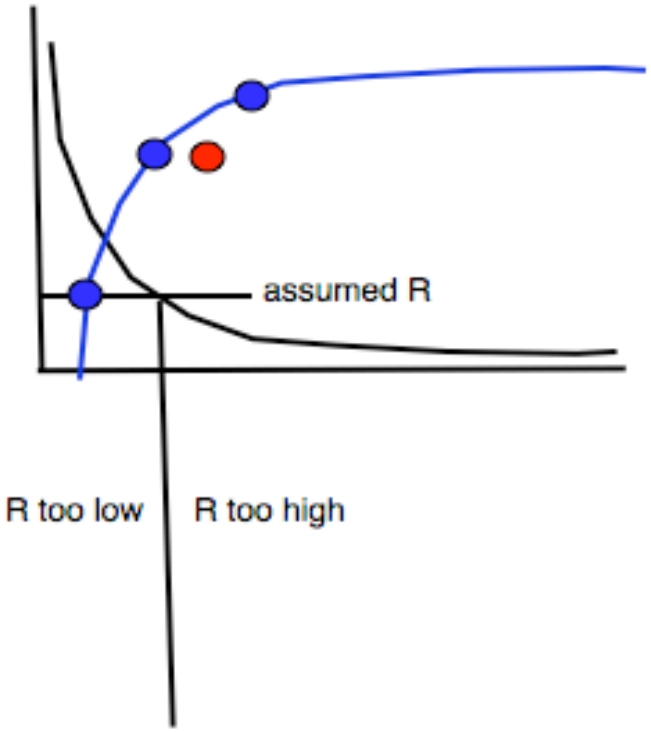
$$R = (\rho_{SPA} - \rho_{nec}) / (t_{SPA} - t_{nec})$$

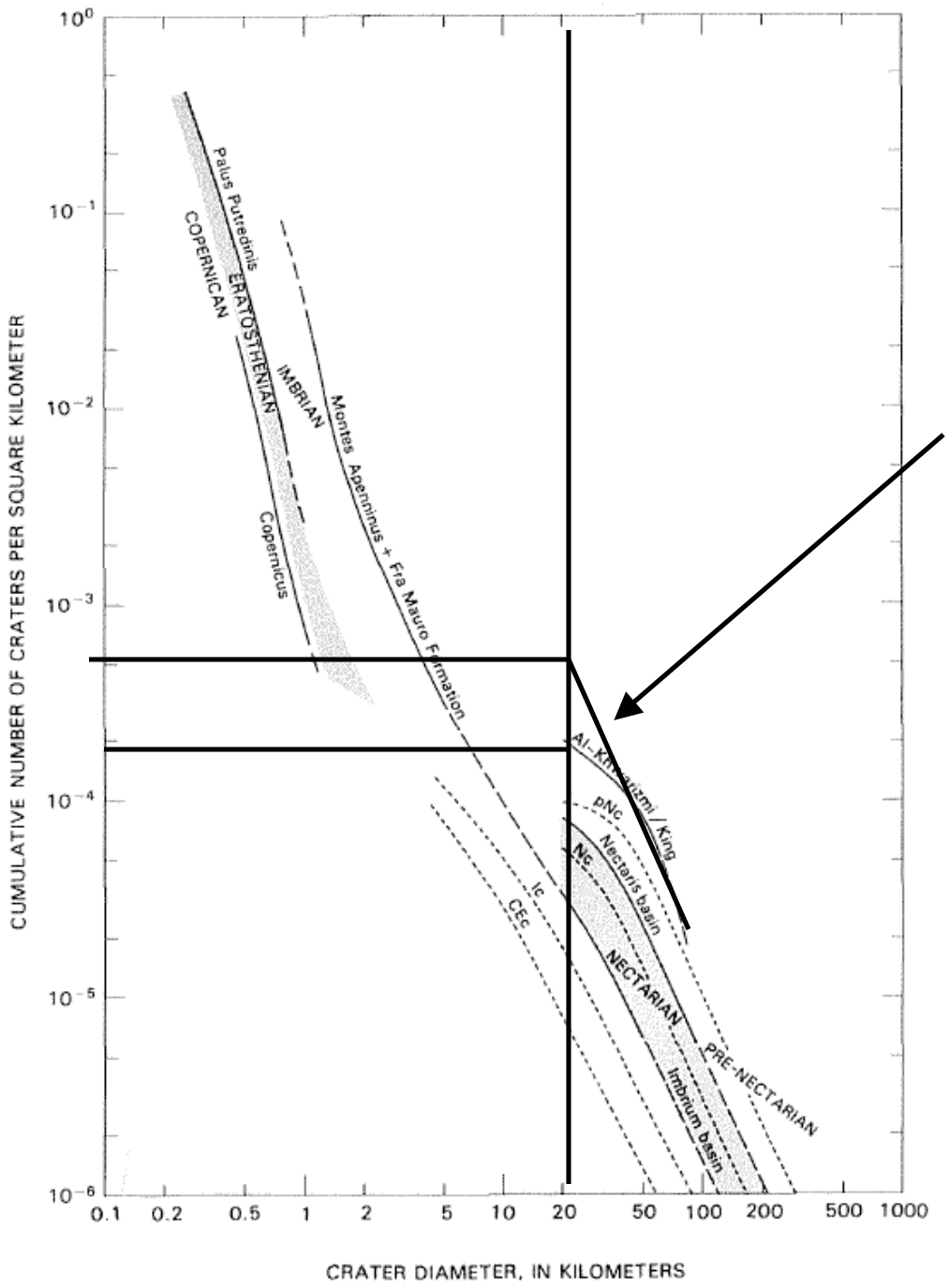
Δt

R too high

correct R

R too low



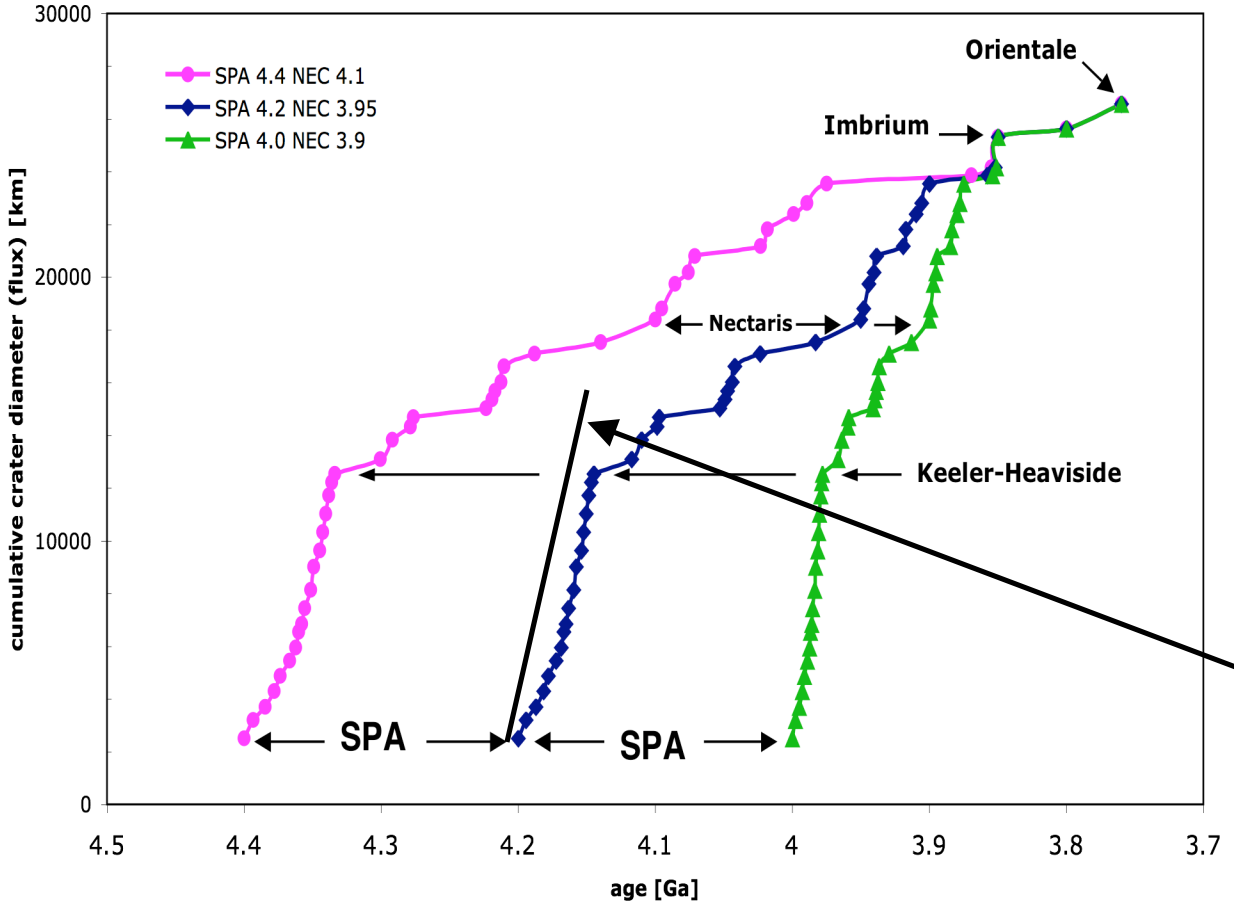


saturation incompleteness

factor of 2 or 3 is size of correction for oldest Pre-Nectarian basins

Incompleteness increases for older basins:

The progress of basin discovery suggests that additional pre-Nectarian basins will be found. Moreover, many basins probably formed before the South Pole-Aitken and Procellarum basins but are now completely obliterated. Basin deposits probably covered all parts of the Moon many times over in the manner displayed by the visible basins.



Wilhelms 1987

Incompleteness corrections steepen earliest part of plot

How big does an impactor have to be before
it will sterilize the earth and "frustrate life"?
Ryder's vision of LHB has no life sterilizing impacts
after the Moon forming impact

Chixulub 65 Mya was diameter ~10 km
energy goes as mv^2
mass goes as $diameter^3$
so a 100 km diameter impactor would have
1000 times the energy

Due to gravitational focusing and larger target size and
higher surface gravity and therefore higher impact velocities
flux on Earth is ~20 times higher. (Hartmann 199?)
Maher and Davidson 1988 cite 250 km diameter impactor
Making an 850 km diameter crator "might sterilize the
whole planet including the ocean bottoms"

"..the Earth will likely suffer ~ 10

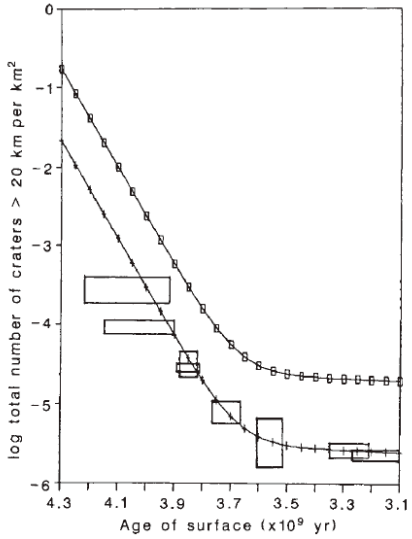


Fig. 1 The lunar and terrestrial cratering history for total number of craters ≥20 km per km^2 as a function of surface age, determined from the relationships in the text. Saturation is neglected. The open boxes represent data from crater surveys from the Moon[4]. The lunar curve was calculated from the terrestrial, assuming a correlation factor of 8 (a result of gravitational focusing and different impact velocities and surface gravities). Symbols: squares, calculated terrestrial; crosses, calculated lunar.